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RESEARCH HIGHLIGHTS

Three-dimensional spintronics: geometry-enabled spin transport and racetrack memory

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Spintronics exploits the electron spin degree of freedom and its coupling to charge and orbital angular momentum as an information carrier, providing an important route to overcome the limitations of conventional electronic devices in terms of power consumption, operating speed, and integration density[1]. Over the past two decades, spintronics research has predominantly focused on two-dimensional (2D) planar thin films and nanowire structures, yielding mature technologies such as magnetic tunnel junctions, spin valves, spin–orbit torque devices, and magnetic random-access memory[2−5]. However, with the continuous downscaling of device dimensions and the increasing demand for system-level integration, planar architectures face intrinsic limitations regarding wiring density, three-dimensional (3D) integration, and multifunctional field coupling.

To address these challenges, expanding into the third spatial dimension has emerged as a transformative research frontier[6−9]. By developing 3D spintronics, this field aims to achieve systematic control of spin transport, magnetic topology, and magnetoelectric coupling within 3D geometrical architectures or multilayer heterostructures. Such 3D configurations not only maximize the effective functional volume within a limited footprint, but also provide a versatile physical platform for vertical spin transport and the stabilization of novel topological states[7−9]. Recent progress in three-dimensional spintronics can be broadly categorized into two major research directions. One direction focuses on geometry-enabled spin transport, where curved and nonplanar magnetic structures are employed to manipulate domain-wall motion and spin transport pathways in three-dimensional space[9−11]. The other direction aims at racetrack memory architectures, where the concept of domain-wall-based memory is extended from planar geometries to fully three-dimensional devices for high-density information storage[12−14]. As illustrated in Fig. 1, these two directions have evolved in parallel and mutually stimulated each other, driving the development of three-dimensional spintronic devices. Motivated by these advances, this work highlights recent breakthroughs in 3D spin transport, emphasizing transport phenomena in complex 3D structures and their translation into 3D interconnect architectures and racetrack memory concepts.

Spin transport in 3D curvilinear geometries. In conventional 2D spintronic devices, spin information is primarily transmitted via in-plane magnetic domain walls, spin waves, or spin-polarized currents. However, in densely integrated systems, such planar schemes inevitably suffer from routing congestion and cumulative power dissipation[12, 15, 16]. By introducing 3D magnetic conduits and spatial routing architectures, 3D spintronics offers novel solutions for vertical magnetic information transfer and geometry-enabled functionalities.

In recent years, magnetic nanowires, helical conduits, and 3D routing structures fabricated using 3D nanofabrication techniques—most notably focused electron beam methods—have been employed to investigate domain-wall dynamics in 3D space. Using focused electron-beam induced deposition (FEBID), researchers fabricated 3D magnetic nanowires[10] (Fig. 2(a)), whose magnetic switching behavior could be directly observed using magneto-optical Kerr effect (MOKE) measurements. It was further revealed that magnetization reversal in these nanowires proceeds via domain-wall nucleation and propagation, demonstrating that magnetic domain walls can stably exist and move in nonplanar and non-straight geometries. These results laid the foundation for subsequent 3D magnetic conduit concepts for spin transport.

Building on this progress, 3D helical magnetic conduits were fabricated using 3D nanoprinting techniques (Fig. 2(b)) to investigate geometry-driven domain-wall transport along nonplanar pathways[11]. By employing X-ray microscopy to image magnetic states under different magnetic-field sequences, robust unidirectional domain-wall motion from the bottom to the top of the helix was observed. Combined experimental and simulation studies revealed that the dominant driving mechanism originates from magnetic energy gradients induced by the large thickness variation along the structure. This work clearly demonstrated the crucial role of 3D geometry in actively governing spin transport, rather than acting merely as a passive channel.

With the maturation of 3D nanofabrication technologies, the scope of 3D spin transport studies has expanded beyond simple ferromagnetic conduits. As shown in Fig. 2(c), focused ion beam (FIB) nanomachining was employed to sculpt single crystals of the magnetic Weyl semimetal $Co_3Sn_2S_2$ into 3D helical structures[17]. It was found that the helical geometry breaks inversion symmetry and, when combined with intrinsic ferromagnetism, gives rise to pronounced nonreciprocal electronic transport far exceeding the classical self-field effect at low temperatures. This enables switchable nonreciprocal

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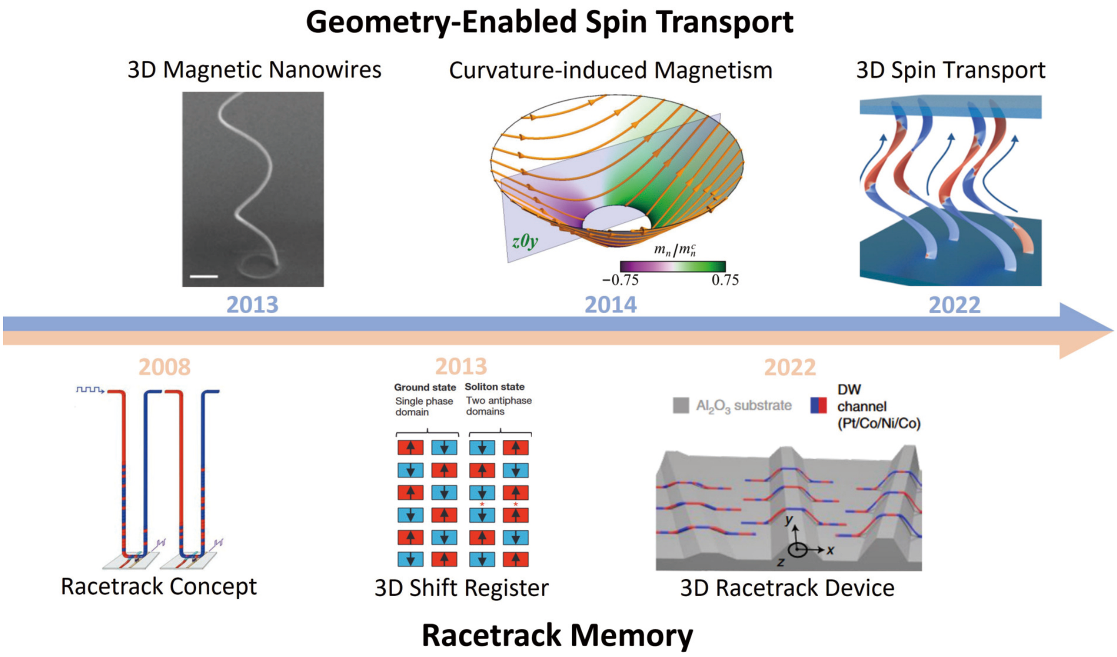

Fig. 1. (Color online) Development of three-dimensional spintronics from two major research directions. The upper panel highlights the evolution of geometry-enabled spin transport, including curvature-induced magnetic effects, three-dimensional magnetic nanowires, and spin transport in curvilinear geometries[9–11]. The lower panel summarizes key milestones in racetrack memory, from the original concept to three-dimensional racetrack memory devices[12–14]. Reproduced with permission. Copyright © 2008, 2013, 2022, Springer Nature. Copyright © 2014, American Physical Society. Copyright © 2022, ACS Publishing.

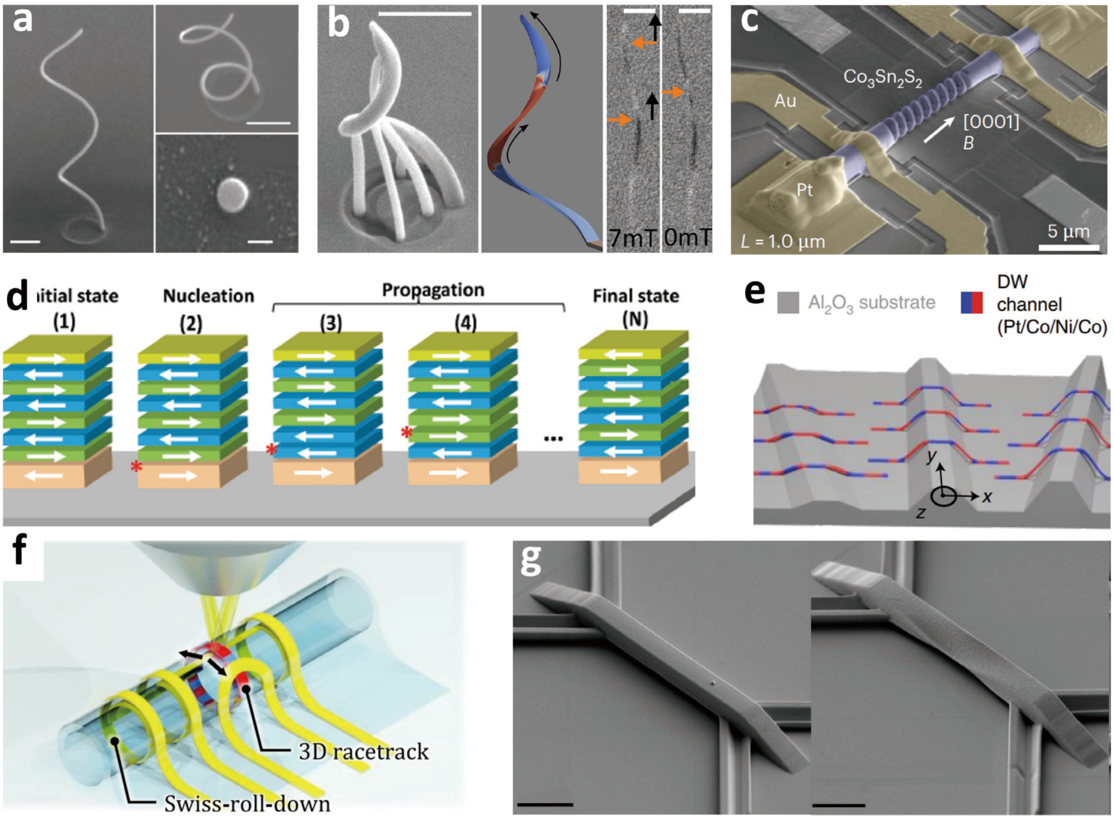

Fig. 2. (Color online) (a) Different views of a double-loop nano-spiral fabricated by FEBID[10]. (b) Scanning electron microscopy (SEM) image of a fabricated 3D magnetic interconnector (left), Simulation snapshots for a model matching the fabricated structure (middle), Shadow X-ray photoemission electron microscopy (XPEEM) snapshots of the magnetization states at 7 and 0 mT (right)[11]. (c) Scanning electron micrographs of nanosculpted $Co_3Sn_2S_2$ helix devices with left-handed chirality[17]. (d) Data operation based on the vertical motion of solitons in multilayered SAFs[18]. (e) Schematic of freestanding racetracks formed from HM/FM heterostructures transferred onto a pretreated sapphire substrate[14]. (f) Schematic of rolled-down 3D device after self-assembling into the "Swiss-roll"[19]. (g) SEM perspective and top view of magnetic ribbons with different twist angles[20]. Reproduced with permission. Copyright © 2018, 2026, 2022, 2024, 2025, Springer Nature. Copyright © 2022, ASC Publishing. Copyright © 2016, Wiley-VCH.

transport (diode-like behavior) in the absence of an external magnetic field. This study highlights the unique capability of 3D geometries to tailor material responses and provides a new pathway for symmetry breaking in intrinsically symmetric materials.

Distinct from complex nanofabrication approaches, multilayer magnetic thin-film systems offer advantages in terms of process compatibility and device scalability, and thus represent another important platform for realizing 3D spin structures. By introducing interlayer exchange coupling, anisotropy gradients, and spatially nonuniform spin–orbit interactions, magnetic configurations can be precisely engineered along the vertical direction. In multilayer synthetic antiferromagnets (SAFs), researchers investigated soliton nucleation and propagation to enable vertical data transfer[18] (Fig. 2(d)). Through combined experimental characterization and simulations, a surface spin-flop transition-triggered soliton nucleation mechanism was revealed, the nonchiral nature of the soliton under external magnetic fields was identified, and the feasibility of information operations based on soliton propagation was demonstrated. These results provide key evidence for vertically functional spin-transport pathways that integrate naturally with multilayer-based stacks.

Realization of 3D racetrack memory. Building on the transport phenomena observed in 3D conduits and multilayers, recent efforts have pivoted toward 3D racetrack memory (3D RTM). In this paradigm, curvilinear and vertical tracks serve simultaneously as information highways and compact storage elements, enabling dense integration beyond planar constraints[13].

3D RTM represents one of the most promising applications of 3D spintronics. In 2022, researchers demonstrated 3D racetrack memory devices by employing a freestanding-transfer technique, in which magnetic heterostructures were fabricated on sacrificial layers and subsequently transferred onto sapphire substrates and pre-patterned 3D protruding architectures[14]. This approach enabled current-induced magnetic domain-wall motion in truly 3D geometries (Fig. 2(e)). Experimental results showed that magnetic domain walls could undergo stable and controllable current-driven motion along 3D tracks. Notably, in synthetic antiferromagnetic (SAF) systems, the influence of 3D geometry on domain-wall velocity and threshold current density was significantly suppressed, indicating enhanced geometric robustness. This work demonstrates that 3D spintronic devices can transition from theoretical concepts to tangible, high-performance implementations, providing a scalable pathway toward high-density 3D memory.

Further advances have explored sophisticated fabrication strategies and 3D architectures for integrated RTM devices[19]. By employing strain-driven self-assembly processes, researchers fabricated 3D Co/Pt stripe heterostructures with well-defined curvature and out-of-plane geometries (Fig. 2(f)). The effects of 3D geometry, strain, and curvature on current-induced domain-wall motion and spin–orbit torque (SOT) efficiency were systematically investigated. Ultimately, fully 3D memory units integrating writing, reading, and storage functionalities were realized. By comparing the performance of 2D and 3D configurations, a pronounced enhancement of SOT efficiency—up to approximately 30%—was observed in the 3D geometry, highlighting a promising route toward next-generation 3D magnetic memory devices.

Magnetic materials exhibit distinct properties when confined to 3D twisted geometries, which has attracted growing research interest for geometry-enabled device functions. Using advanced lithographic techniques, researchers fabricated 3D twisted magnetic ribbons (Fig. 2(g)) to investigate the interplay between geometrical chirality and spin chirality in current-induced domain-wall motion[20]. The results revealed that in curved and twisted 3D structures, geometry itself can induce effective chiral interactions, thereby influencing domain-wall configurations, propagation direction, and dynamical behavior. These findings confirm that geometry in 3D spintronic systems is not merely a passive structural constraint, but an active degree of freedom for tailoring spin transport along tracks and for enabling novel functionalities within 3D routing networks.

This work has navigated the rapidly evolving landscape of 3D spintronics, highlighting the pivotal transition from planar confinement to three-dimensional freedom. As we have discussed, the introduction of the third spatial dimension does more than merely increase integration density; it fundamentally alters the physics of spin transport. By exploiting geometry-induced effects, such as curvature-driven effective fields and chiral symmetry breaking, 3D spintronics offers a versatile playground for tailoring magnetic states and optimizing domain-wall dynamics in ways that are physically forbidden in 2D counterparts.

Despite these promising advances, bridging the gap between proof-of-concept prototypes and mass-fabrication technologies remains a formidable challenge. A primary bottleneck lies in fabrication scalability. While techniques like FEBID and focused ion beam sculpting have been instrumental in fundamental studies, they lack the throughput required for mass production. The future of the field arguably rests on the development of CMOS-compatible 3D manufacturing strategies, such as advanced self-assembly of multilayer heterostructures and vertical chemical synthesis, which can reconcile the high crystalline quality required for efficient spin transport with the geometric complexity needed for high-density storage.

Furthermore, the operational robustness of 3D devices demands a deeper understanding of complex physical couplings. Thermal management, for instance, will become critical as device density scales vertically, requiring novel dissipation strategies within 3D lattice frameworks. Simultaneously, precise control over domain-wall synchronization and pinning in curvilinear tracks is essential to prevent data drift in racetrack memories. Addressing these issues necessitates not only theoretical breakthroughs but also the evolution of metrology tools, specifically non-destructive, time-resolved 3D magnetic imaging techniques capable of probing buried interfaces and dynamic spin textures in real time.

Looking forward, the scope of 3D spintronics extends beyond conventional memory and logic. The intersection of 3D geometry with non-trivial topology—exemplified by the exploration of 3D Weyl semimetals and skyrmion tubes—heralds a new era of "topological spintronics" where information is protected by topology rather than material hardness. Moreover, the interconnectivity inherent in 3D networks naturally mimics biological neural architectures, positioning 3D spintronics as a prime candidate for neuromorphic computing. Ultimately, by synergizing materials science, topology physics, and nanofabrication, 3D spintronics is poised to redefine the limits of post-Moore computing architectures.

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